ASSESSMENT OF CRUSHED SALT CONSOLIDATION AND FRACTURE HEALING IN A NUCLEAR WASTE REPOSITORY IN SALT

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ABSTRACT

An assessment is made of the degree to which consolidation of crushed salt backfill and fracture healing might enhance the waste isolation capabilities of a high-level waste repository in salt. The paper reviews the properties of crushed salt and the nature of fracture healing as known from laboratory testing and presents analytical methods for predicting the rates at which the processes will occur in a repository. The rate at which crushed salt consolidation will occur is found to be highly uncertain because of contradictory evidence from laboratory testing regarding the creep consolidation characteristics of crushed salt. Moreover, the consolidation rate is likely to vary considerably from one site to another due to differences in room closure rates resulting from differences in the creep characteristics of intact salts. Present indications are that consolidation to low porosities should occur within hundreds of years at most candidate repository sites for locations within the repository close to the waste. Fracture healing should occur relatively rapidly, within tens to hundreds of years, as the confining stress across the fractures approaches lithostatic levels. Healing of fractures caused by excavation may be enhanced by placing relatively rigid concrete plugs in the tunnel openings.

INTRODUCTION

Two aspects of salt behavior may contribute favorably to waste isolation in a nuclear waste repository in salt:

- o Consolidation of crushed salt backfill over time due to creep closure of the underground openings, resulting in a backfill barrier with very low permeability.
- o Healing of fractures (created by excavation) around the underground openings with time, restoring the salt to the low permeability of the intact salt state.

If effective within reasonable time periods (tens to hundreds of years), these processes will result in encapsulation of the wastes in an essentially impermeable, homogeneous salt monolith, thus reducing the long-term requirements for other parts of the seal system, and enhancing the general confidence regarding the isolation capabilities of the site as a whole.

The purposes of this paper are to review the status of knowledge regarding crushed salt consolidation and fracture healing and to provide preliminary analyses which predict the rates of consolidation and healing under repository conditions. A more detailed description of the contents of the paper will be given in a forthcoming report to be published by the Office of Nuclear Waste Isolation.

PROPERTIES OF CRUSHED SALT

Density and Compaction Characteristics

As an example of the type of material which will be available for use as crushed salt, density and compaction characteristics have been determined for crushed salt produced by a roadheader-type continuous mining machine at the Waste Isolation Pilot Plant (WIPP) site in southeastern New Mexico. The salt was sampled from immediately behind the machine excluding occasional large pieces which had fallen from the tunnel walls and which had not been processed by the machine. In situ, the crystal size of the salt is in the range 5-15 mm and the insolubles content is about 1.5%.

As shown by the following table, the range of grain size for the crushed material was 75 mm to about 0.05 mm.

TABLE I

Particle size distribution of crushed salt from WIPP

Particle Diameter (mm)	% Passing
75	100
6	80
3.4 (D_{60})	60
1.8	40
0.7	20
0.3 (D_{10})	10
0.05	2

Coefficient of uniformity (D_{60}/D_{10}) = 11.3

Compaction tests were conducted on the as-received material with the material coarser than 19 mm removed. The minimum density, determined by pouring the salt into a container without compaction, was 1.30 g/cm^3 (81.0 pcf) corresponding to a porosity of 40.3%. After compaction dry by the standard Proctor method (ASTM D698) the porosity was reduced to 24.8%.

Deformability

Quasi-static compaction and creep consolidation characteristics of crushed salt have been measured in laboratory tests by Ratigan and Wagner (1978) and Holcomb and Hannum (1982). Ratigan and Wagner's tests were conducted on Avery Island salt which was uniformly graded with a maximum particle size of about 1.0 cm. Cylindrical samples, 8.9 cm in diameter and 20.3 cm in length, were loaded triaxially in hydrostatic compression at stresses up to 13.8 MPa and temperatures up to 52°C. Each sample was loaded quasi-statically and then allowed to creep for various periods up to 13 days. Total volumetric strains up to 37% and porosities as low as 6% were observed. Holcomb and Hannum's tests were conducted on salt from WIPP and a potash mine in New Mexico which had a grain size distribution similar to that described in the previous section. Cylindrical samples, 10.4 cm in diameter and 14.6 cm in length, were tested in pure hydrostatic compression at stresses up to 21 MPa and temperatures up to 100°C for periods up to 3 days. Final porosities were as low as 12%.

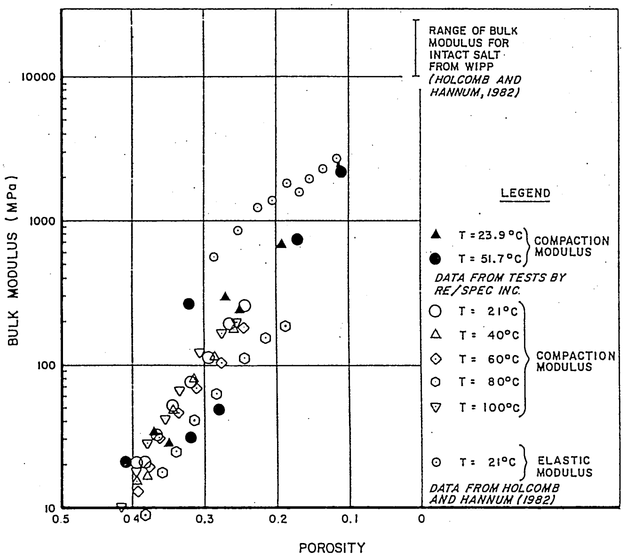
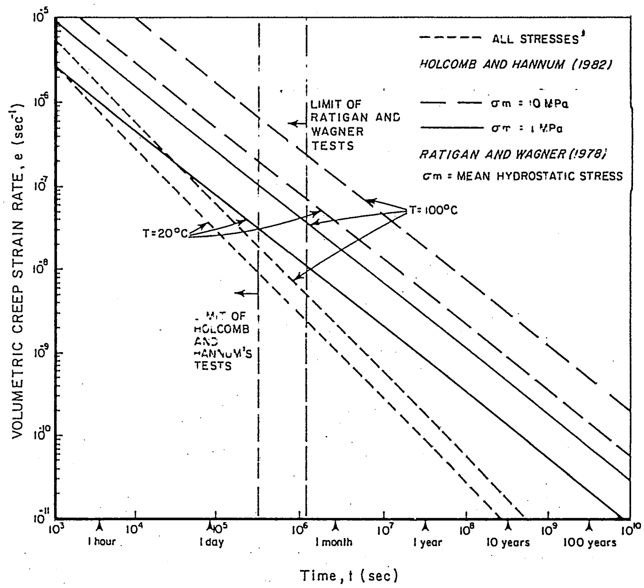


Fig. 1. Bulk Modulus of Crushed Salt as a Function of Porosity

Test results from Ratigan and Wagner and Holcomb and Hannum are compared in Figure 1, which shows bulk modulus as a function of porosity and Figure 2, which shows creep strain rate as a function of time. The bulk modulus data are essentially the same from the two testing programs. Holcomb and Hannum report "elastic moduli" obtained from reloading tests. These tend to be higher than the moduli obtained from initial loading, indicating the importance of particle rearrangement during compaction. As shown by Figure 2, the creep strain rates obtained by Holcomb and Hannum decrease more rapidly with time than those obtained by Ratigan and Wagner. At large times, the difference in creep rates is one to two orders of magnitude. As discussed later, this has a major effect on the predicted rates of backfill consolidation in a repository. The difference in the creep rates is not explained, although it may be related to differences between the two types of salt or to differences in test technique. It is also noted that all of the creep tests reported were of relatively short duration.



* VOLUMETRIC CREEP STRAIN RATE FOUND TO BE INDEPENDENT OF STRESS WITHIN TEST RANGE 1.7 - 10.1 MPa

NOTE: DATA EXTRAPOLATED BEYOND 3 ½ DAYS (HOLCOMB & HANNUM) OR 13 DAYS (RATIGAN AND WAGNER)

Fig. 2. Volumetric Strain Rate of Crushed Salt as a Function of Time

Permeability

Shor et al. (1981) consolidated crushed salt in brine and obtained a relationship between permeability, porosity, and average initial particle size. According to this relationship, permeability decreases more rapidly with decreasing porosity than would be predicted using the Blake-Kozeny relationship developed for sands. Shor et al considered this to be evidence of sintering (i.e., bonding between grains) during the consolidation process.

The above relationship developed by Shor et al. utilized crushed salt in which the initial particle size for various mixes ranged from 0.01 to 0.03 cm. This relationship is used to construct a lower bound intrinsic permeability vs. porosity curve for an average initial particle size of 0.02 cm (Figure 3). Also shown in Figure 3 is an intrinsic permeability-porosity relationship calculated using Shor et al's relationship extrapolated to an average particle size of 0.34 cm. This particle size falls outside Shor et al.'s experimental range but corresponds to a typical backfill. Because intrinsic permeability is related to the square of average particle size, the curve based on the larger particle size results in intrinsic permeabilities two orders of magnitude greater than the lower bound predictive curve.

Figure 3 also shows a *regression* curve for porosity-permeability data obtained from intact rock salt (in the range 0.02 to 0.06 porosity). The regression analysis indicates a similar trend to the empirical relationship developed by Shor et al. with differences attributable to factors such as different average grain sizes, grain size distributions, stress and temperature histories, and probably sample disturbance. The results indicate that the combined effects of reduction in void space and sintering during consolidation can result in very low permeabilities, approaching or equaling values for intact rock salt. Low permeabilities are achieved, however, only at low porosity values.

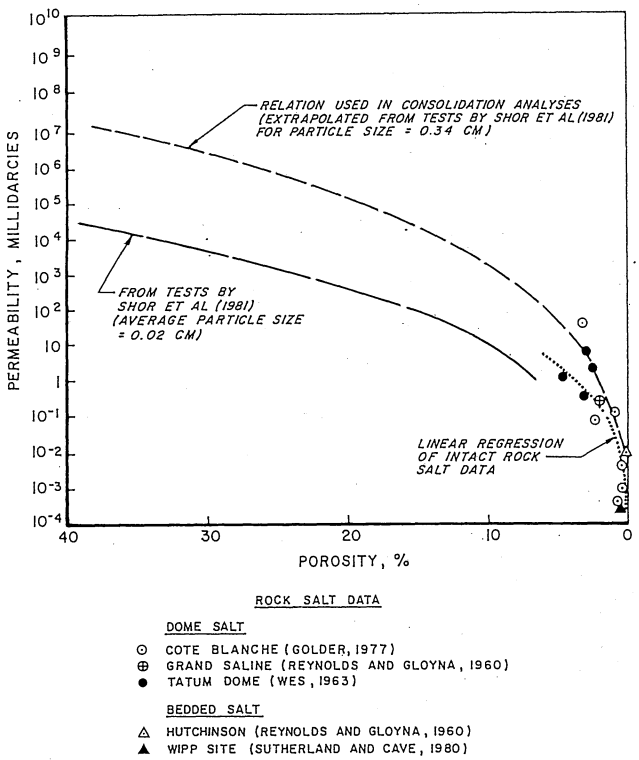


Fig. 3. Permeability of Intact and Crushed Salt as a Function of Porosity

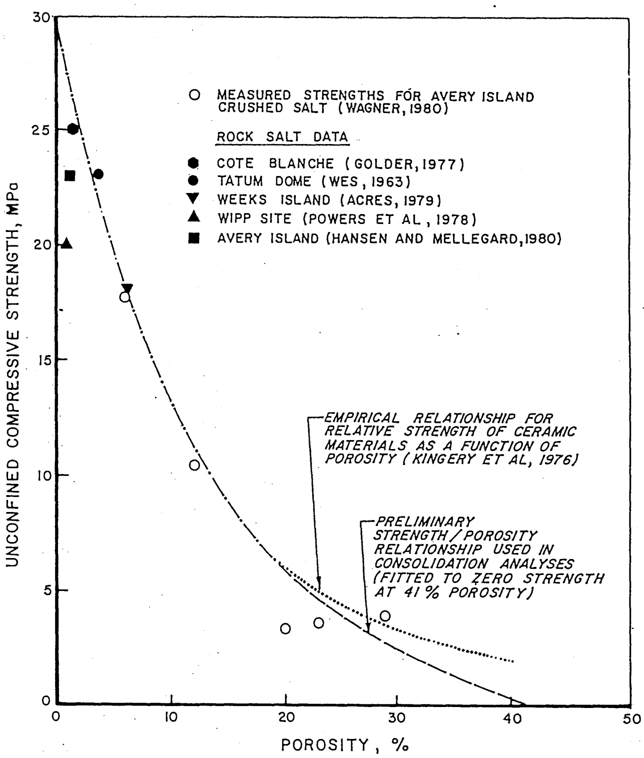


Fig. 4. Unconfined Compressive Strength of Intact and Crushed Salt as a Function of Porosity

Strength

Unconfined compressive strengths measured on consolidated crushed salt from Avery Island are reported by Wagner (1980). These data are replotted in Figure 4, normalized against porosity. Also included are test data obtained from testing of intact rock salt from four dome sites (Avery Island, Cote Blanche, Tatum, Weeks Island) and one bedded salt site (WIPP). In the range of porosity below approximately 0.2 to 0.3, the data generally fit well to a curve obtained from Kingery et al. (1976) which relates porosity to relative strength (strength at zero porosity = 1) for ceramic materials. This relationship provides further evidence that the process of sintering may play a role in the consolidation process, in that the crushed salt appears to behave as a porous solid rather than as a densely compacted granular material.

ANALYSIS OF THE RATE OF CONSOLIDATION OF EMPLACED CRUSHED SALT BACKFILL

Analytical Method

An analytical method has been developed to calculate changes in porosity, permeability and strength of crushed salt backfill as functions of time. Essentially, for any specific location in the repository, the iterative analysis includes the following major steps:

1. Calculate temperature history, considering waste type and loading, location in the repository, and thermal properties.
2. Calculate volumetric strain (closure) incorporating the temperature history (obtained from step 1) and pressure in the backfill (obtained from step 7). Closures are calculated using a closed-form solution for a circular opening.
3. Calculate change in porosity of the backfill from the volumetric strain of the opening obtained from step 2.
4. Calculate the increment of creep consolidation of the backfill according to creep characteristics of the crushed material (obtained from laboratory tests) and the stress (step 7) and temperature (step 1).
5. Calculate the increment of "elastic" volumetric strain as the difference between the total strain (step 2) and the creep strain (step 4).
6. Calculate the bulk modulus of the backfill from the calculated volumetric strain (step 2) and relationships between bulk modulus and volumetric strain (or porosity) obtained from the literature.
7. Calculate the internal pressure in the backfill as the product of the elastic strain and the bulk modulus.
8. Calculate permeability and strength from relationships with porosity obtained from laboratory tests.

The analysis is repeated for time steps of one year until the porosity of the crushed material attains a value (0.6%) equivalent to the porosity of intact salt.

Temperature Histories at Seal Locations

Heat transfer analyses have been performed to determine temperature histories for various potential seal locations at intervals following waste emplacement (Figure 5). The analyses calculate the temperature increases due to waste emplacement above the ambient temperature at the repository depth, using the following approach:

- Analyses are based on the superposition of closed-form analytical solutions for linear heat conduction from infinite strip power sources in the plane of the repository, surrounded by an infinite medium.

- Thermal properties (obtained from Callahan, 1981) are constant with respect to temperature; values used are as follows:

  - thermal diffusivity 2.91×10^{-6} m^2/s
  - thermal conductivity 5.36 W/m^2K

- Thermal properties are isotropic and homogeneous throughout the rock mass (i.e., no allowance is made for interbeds in the salt or for a change in lithology above the salt within the zone of influence of the repository).

- Backfill materials are assigned the same thermal properties as the host rock.

The effect of modeling the repository by superimposing a number of infinite strip sources is to over-predict peak temperatures. Conversely, the analyses neglect the possible insulating effects of non-salt strata above or below the repository. Accordingly, the error in the simplified analyses is considered to be minor.

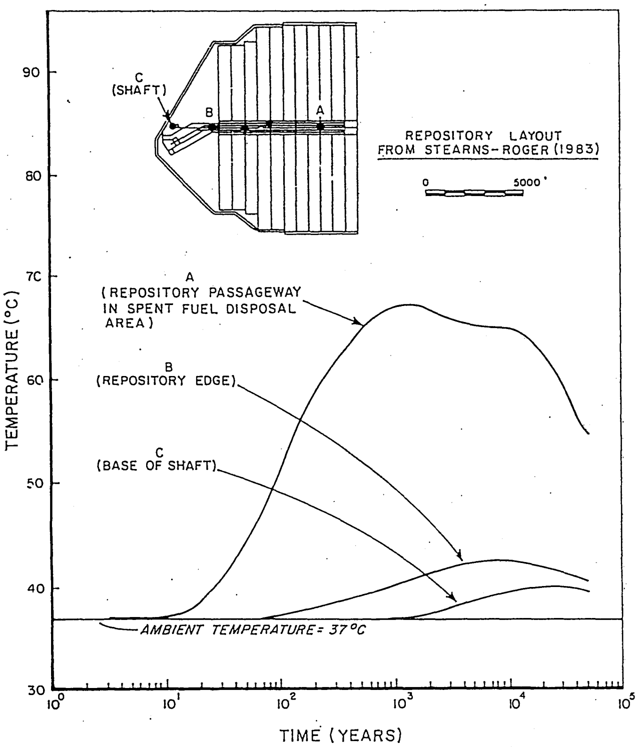


Fig. 5. Approximate Temperature Histories for Potential Seal Locations - Permian Basin Repository

Closure Rates

The driving mechanism for consolidation of the salt backfill is closure of the shaft or tunnel due to salt creep. Simplified analyses of room closure have been performed using a closed-form solution for radial displacement of an infinitely long cylindrical opening in an infinite medium. The closed-form solution accounts for secondary creep which is dependent on both stress and temperature. The general solution for the rate of radial displacement (w) at any radius is:

$$w = -E_c\left(\frac{\sqrt{3}}{2}\right)^{n+1}\left(\frac{2a^{2/n}(P_o - P_i)}{n\sigma_c\, r^{2/n}}\right)^n r \qquad (1)$$

where:

E_c = A exp(-Q/RT),
A = creep constant,
Q = activation energy,
T = absolute temperature,
R = universal gas constant,
n = stress exponent,
σ_c = constant used to normalize stress in creep law,
a = radius of the penetration,
r = radius,
P_o = far-field stress, assumed to be hydrostatic, and
P_i = internal radial stress applied to the surface of the penetration.

For the condition in which the internal stress is zero, the displacement rate (i.e., closure rate) at the surface of the opening is given by:

$$w = -E_c\left(\frac{\sqrt{3}}{2}\right)^{n+1}\left(\frac{2P_o}{n\sigma_c}\right)^n a \qquad (2)$$

The constants A, Q, and n are obtained from laboratory testing. Values for candidate repository sites are given by Pfeifle et al. (1983).

Predicted Rate of Consolidation for a Repository in the Permian Basin

Analyses have been conducted for candidate repositories in the Permian Basin, Paradox Basin and Richton Dome. The following input parameters were used for analysis of a repository in the Permian Basin:

- Repository depth - 727m (2384 feet)
- Far field in situ stress - 16.4 MPa (2384 psi)
- Ambient temperature at repository depth - 37°C
- Initial backfill porosity - 41%
- Porosity of intact salt - 0.6%
- Creep properties of intact salt - from Pfeifle et al. (1983)
- Mechanical properties of crushed salt - from Ratigan and Wagner (1978)

Figure 6 shows the results obtained for three locations in the repository and for two types of salt, Permian Unit 4 and Permian Unit 5. Note that the salt properties varied in the analysis are the creep properties of the intact salt which determine the tunnel or shaft closure rate. The properties of the crushed salt for all the cases shown in Figure 6 are obtained (for Avery Island dome salt) from Ratigan and Wagner (1978). All analyses are for an idealized circular opening.

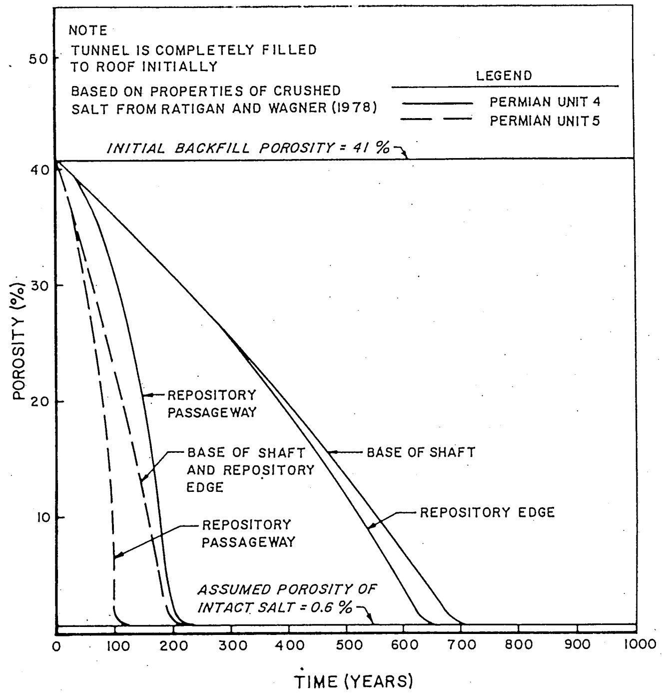


Fig. 6. Reduction in Porosity of Crushed Salt Due to Creep Consolidation at Various Seal Locations - Permian Basin Repository

The analyses illustrated in Figure 6 indicate that full consolidation (to a porosity of 0.6%) could take from 100 to 700 years depending on location within the repository and, importantly, on the creep rate of the intact salt. Additional analyses show that the consolidation rate is highly sensitive also to the creep properties of the crushed salt. Figure 7 shows a comparison between consolidation predicted using Ratigan and Wagner's creep properties of crushed salt (as also shown in Figure 6) and consolidation predicted using Holcomb and Hannum's creep properties of crushed salt. Using Ratigan and Wagner's data, the crushed salt creeps sufficiently rapidly to prevent pressure build-up in the backfill and the consolidation rate is only slightly slower than the closure rate of an empty room. Conversely, with Holcomb and Hannum's data, the crushed salt creeps very slowly and pressure builds up in the backfill as it stiffens due to compaction. This pressure build-up effectively prevents further room closure and backfill consolidation other than at a very slow rate.

Other factors influencing consolidation rate include repository depth (as it affects in situ stress and temperature), type of waste and location within the repository (as they affect temperature), the initial porosity of the backfill (as affected by compaction and any gap left below the roof of a tunnel) and moisture content (as discussed below).

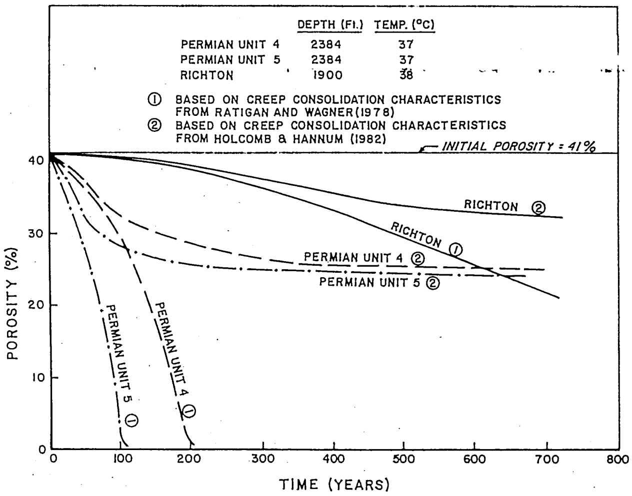


Fig. 7. Influence of Creep Consolidation Characteristics on Consolidation Rate

CURRENT ASSESSMENT OF THE RATE AND EFFECTIVENESS OF CRUSHED SALT CONSOLIDATION IN A REPOSITORY

The above analyses indicate that consolidation of crushed salt backfill may be a viable process for encapsulation of waste within a period of hundreds of years. Current uncertainty regarding consolidation rates stems from three sources.

1. As noted above, the creep properties of the crushed salt have a major influence on the rate of consolidation. Creep within the backfill is required to prevent pressure build-up in the backfill. At present, there is a significant discrepancy between two data sets regarding the creep properties of crushed salt. One data set indicates a relatively fast creep rate such that for most sites, and most locations in a repository, effective consolidation would occur within a few hundred to several hundred years. Conversely, the other data set indicates a much slower creep rate, such that effective consolidation would not occur within several thousands of years.

2. Provided that the backfill will creep sufficiently to allow consolidation to proceed, the major factor determining the consolidation rate is the closure rate of the room or tunnel. This in turn is determined by the depth of the repository, by the ambient temperature at repository depth, by proximity to heat-generating waste, and by the creep properties of the salt. Analysis of laboratory test data indicates that there is a variation of 2-3 orders of magnitude in the secondary creep rates of salts from different candidate repository sites (Nelson and Kelsall, 1984). Whereas Permian Basin salt appears to creep at a relatively fast rate, other salts such as from Richton Dome appear to creep at a relatively slow rate. Accordingly, the rates of consolidation might vary substantially according to the repository location.

3. The ultimate degree of consolidation might be affected by brine slowly seeping out of the salt and collecting in the voids in the backfill. At present it is not possible to make a direct comparison between the rates of consolidation and brine inflow, neither of which can be determined with certainty. Laboratory testing is required to determine the influence of brine on consolidation. Possibly, as suggested by tests by Shor et al. (1981) the presence of brine might enhance the consolidation process. Alternatively, a large inflow could fill the voids in the backfill and inhibit consolidation.

It is concluded that there is significant uncertainty at present regarding the effectiveness of the consolidation process. Confidence in the effectiveness of the consolidation process within a period of interest to waste isolation (i.e., less than about 1000 years) is greatest for sites with relatively fast-creeping salt, for relatively deep repositories, for high-level waste repositories, and for locations in a repository close to heat-producing waste.

Prior to license application for repository construction the uncertainty in predicted consolidation rates should be greatly reduced by: 1) long-term laboratory testing to determine the creep properties of crushed salt; 2) long-term laboratory testing to increase the data base for creep of intact salt; 3) field testing to validate creep properties; and 4) analysis of the possible rates of water inflow to a repository in salt. Laboratory testing of crushed salt is currently in progress by D'Appolonia and Sandia National Laboratories.

FRACTURE HEALING

While in situ salt is likely to be unfractured in the natural state, fractures may be created in a "disturbed zone" surrounding a shaft or tunnel by blasting or by slabbing in response to stress relief. If a relatively rigid plug is placed in the shaft or tunnel, the stress in the disturbed zone will increase in response to creep of the salt against the plug. It is anticipated that this increase in stress, coupled with any increase in temperature following waste emplacement, will result in effective fracture healing.

Tests to evaluate fracture healing in salt have been conducted by Costin and Wawersik (1980). Short rod specimens fabricated from intact WIPP salt were loaded in tension to failure, creating a fracture along the axis of the specimen. After fracturing, the specimens were pieced back together and subjected to higher temperatures (up to 100°C) and pressures (up to 35 MPa) to "heal" the fracture. The specimens were then retested to determine the degree to which the fractures healed. Results indicated that significant healing (70-80% of original strength) occurred within a few days for all conditions except the lowest temperatures and pressures. The tests evaluated fracture healing in terms of fracture toughness, a parameter which indicates the resistance to crack propagation along an existing fracture. The results do not indicate permeability directly, although it appears likely that permeability should be reduced significantly along fractures which exhibit high values (approaching values for intact specimens) for fracture toughness. In the test with the lowest temperature and confining stress (22°C, 10 MPa) the strength along the fracture was in the range 20 to 30% of the intact strength. This might be considered an encouraging result given the short duration of the test.

Investigations of the flow of brine along interfaces in salt have been performed by Gilpatrick et al. (1982). This work is important to the subject of fracture healing because it provides insight to the dependence of fracture permeability on stress state and time. Measurements were made of the radial flow of brine through the interface between two artificially prepared cylindrical salt crystals. Optical quality sodium chloride crystals were used, subjected to stresses up to 14 MPa and temperatures up to 80°C. The permeability of the interface was observed and found to decrease linearly with the reciprocal of the flow time; i.e., the permeability decreased with time under constant conditions. It was postulated that pressure solution effects in the brine were responsible for the decrease in permeability with time.

At present, it is not possible to perform a direct analysis of the rate of fracture healing in repository conditions. It is possible, however, to model the rate at which stresses will build up on concrete or salt bulkheads placed in salt using an approach method similar to that used to model crushed salt consolidation described above. In this case, in the analysis of closure rate of an opening (Equation 1), the internal pressure P_i is updated by adding the incremental stress ΔP_i computed by the following expression:

$$\Delta P_i = E \, \Delta u/a \qquad (3)$$

where E is the elastic modulus of the bulkhead material, Δu is the incremental change in radial closure, and a is the radius of the penetration based on the deformed geometry. In this analysis, the "elastic modulus" used is the Young's modulus. In reality, the appropriate modulus would be a constrained modulus which would be larger than the Young's modulus. Use of Young's modulus is conservative in predicting lower radial stresses.

For Permian salt, and concrete with a modulus of 27.6 GPa, the radial stress reaches 50% of the initial in situ stress in less than 1 to 5 years, depending on the salt unit analyzed and on the location in the repository. Even with a relatively slowly creeping salt (e.g., Richton), and for locations removed from the waste, the stress build-up on a concrete plug is predicted to be relatively rapid. Based on the limited testing of fracture healing described above, it can be reasonably concluded that any fractures in the salt adjacent to a bulkhead placed in a penetration should be at least significantly closed, if not totally healed, within a period of tens of years following bulkhead construction. Laboratory tests of fracture healing, in which permeability will be measured directly, are in progress by D'Appolonia.

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